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Magnetic Pulsations at the Quasi-Parallel Shock

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The plasma and field properties of large-amplitude magnetic field pulsations upstream from the quasi-parallel region of the Earth's bow shock are examined in high time resolution using data from ISEE 1 and 2. The relative timing of the magnetic field profiles observed at the two spacecraft shows that some of the pulsations are convecting antisunward across the spacecraft while others are brief out/in motions of the bow shock across the spacecraft. Pulsations with both timing signatures are the site of slowing and heating of the solar wind plasma. The ions tend to be only weakly heated in the convecting pulsations, while within the out/in pulsations the ion heating can be quite substantial but variable. This variation occurs not only from pulsation to pulsation but also from point to point within a given pulsation. In general, the hottest distributions within the out/in pulsations tend to occur in regions of lower density and field strength. Magnetic pulsations bear a number of similarities to previously identified hot diamagnetic cavity events as well as to more durable crossings of the quasi-parallel shock itself. These various phenomena may be different manifestations of the same basic physical processes, in particular the coupling of coherently reflected ions to the solar wind beam.

INTRODUCTION

Large-amplitude magnetic field pulsations are a common feature of the region upstream from the quasi-parallel portion of the Earth's bow shock, in which the average upstream magnetic field direction lies within about 45° of the average shock normal direction [*Greenstadt et al.*, 1970*a*,*b*, 1977]. The pulsations typically last for ~1 to a few minutes at a particular point in space and are embedded in the general low-frequency, MHD-like, upstream wave activity commonly associated with the quasi-parallel shock. This wave activity is associated with backstreaming "diffuse" suprathermal ions of bow shock origin [e.g., *Paschmann et al.*, 1979]. An example of such pulsations is illustrated in Figure 1, which shows magnetic field measurements made by the ISEE 2 fluxgate magnetometer [*Russell*, 1978] during a 1-hour interval near an outbound crossing of the bow shock on September 1, 1979. After the shock crossing, which occurred just before 0710 UT, the spacecraft was in the upstream solar wind, and the compressive, low-frequency (~0.03 Hz in the spacecraft frame) field fluctuations are clearly evident, both in the individual components and in the total field strength. The brief intervals of significantly elevated field strength (e.g., ~1724, ~1733, and ~1737 UT) are the magnetic pulsations of particular interest for the present paper.

Two-spacecraft studies have suggested that the upstream region in which pulsations such as those exhibited in Figure 1 exist may be $\gtrsim$1 to a few Earth radii thick [*Greenstadt et al.*, 1970*a*, 1977] and that the individual pulsations have a correlation length of roughly 800 km [*Greenstadt et al.*, 1982]. This correlation length is comparable to the gyroradius of typical backstreaming suprathermal ions of bow shock origin. Certain aspects of the plasma and wave properties of the pulsations were examined by *Greenstadt et al.* [1977], who used magnetic field, plasma wave, and ion data from the HEOS 1 and OGO 5 spacecraft (no electron measurements were available). Although the ion measurements used in that study were strongly time-aliased (the full spectral measurement required 384 s, with four 96-s subcycle spectra acquired at one fourth the energy resolution of the full spectrum), the ion distributions within the pulsations were found to be temporally variable and different from either the surrounding solar wind or the clearly shocked magnetosheath plasma. Only modest proton heating was observed within the pulsations. The bulk flow velocity was only marginally slower than in the unshocked solar wind, but appreciable flow deflections (~20°-40°) were observed. Additionally, *Greenstadt et al.* [1977] identified an "interpulsation regime" which occurred between larger-amplitude pulsations. Within the interpulsation regime the magnetic field characteristics were nearly identical to those in the normal, lower-amplitude waves, but there was some suspicion of a different spectral character to the ions.

Beyond these facts, little is known about the nature of the magnetic pulsations and of the role they play in the quasi-parallel shock transition. In particular, it is not known whether they are (1) extremely amplified and steepened versions of upstream waves which are convected past the spacecraft by the solar wind, (2) signatures of rapid expansions and contractions of a relatively large-scale coherent "shock surface," or (3) something entirely different, perhaps related to the formation (or reformation) of the shock itself in the quasi-parallel geometry, as suggested by recent numerical simulations [*Burgess*, 1989; V. Thomas et al., manuscript in preparation 1989].

Our purpose here is to examine the nature of these pulsations by investigating their plasma and field properties in greater detail and in much higher temporal resolution than was possible in earlier studies. We use measurements obtained by the Los Alamos/Garching Fast Plasma Experiments (FPE) [*Bame et al.*, 1978] and the UCLA flux gate

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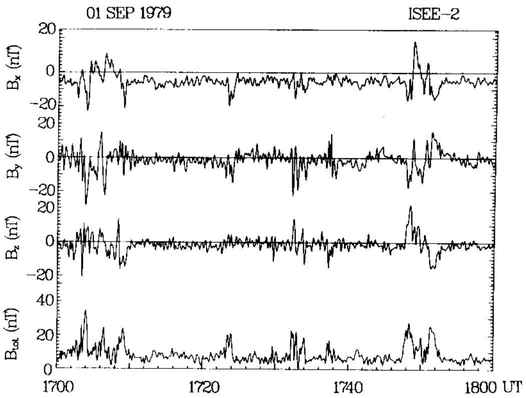

Fig. 1. Magnetic field components (GSE coordinates) and total field magnitude measured by the ISEE 2 flux gate magnetometer near an outbound crossing of the Earth's bow shock on September 1, 1979. The shock was crossed just before 1710 UT, and thereafter the spacecraft was in the upstream solar wind. The compressive, low-frequency magnetic field fluctuations evident throughout the interval are characteristic of the region upstream from the quasi-parallel bow shock. The brief intervals of significantly elevated field strength at ~1724, ~1733, and ~1737 UT are what has been termed "magnetic pulsations." The event centered at ~1750 UT is a hot diamagnetic cavity which has been previously described in the literature [*Thomsen et al.*, 1988].

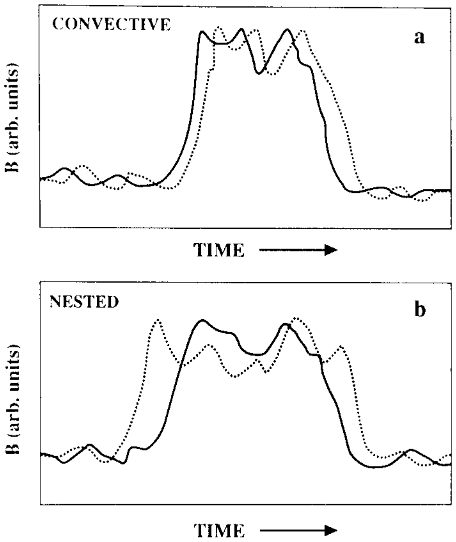

Fig. 2. Schematic magnetic field signatures at two separated spacecraft (lighter and heavier traces) observing structures which are *(a)* convecting past the spacecraft, or *(b)* moving out and then back in again past the spacecraft.

magnetometers [*Russell*, 1978] on the coorbiting ISEE 1 and 2 spacecraft. In one 3-s spin of the spacecraft, the FPE measures the two-dimensional ion and electron distributions at 16 energies x 16 azimuthal angles. In high data rate, distributions are obtained every 3 s, whereas in low data rate one 3-s distribution for each species is obtained every 12 s. The magnetometers obtain a vector magnetic field measurement 16 times each second in high data rate and 4 times each second in low data rate.

One particular goal of this paper is to try to distinguish between at least the first two of the possibilities mentioned above (namely, free-standing structures which propagate or convect past the spacecraft versus out/in oscillations of a semicoherent shock surface) by taking advantage of the two-spacecraft ISEE measurements to determine the direction of motion of the pulsations. Specifically, in the case of a pulsation propagating or convecting past the spacecraft, both the entrance to and the exit from the pulsation will be delayed in time at one spacecraft relative to the other, as illustrated schematically in Figure 2*a*. The time delay between the signatures at the two spacecraft is a measure of the speed of the structure. Such a temporally offset signature is what we call "convective." By contrast, bow shock motion out over the satellites will be seen first by the spacecraft closest to the Earth. That same spacecraft will also be the last to see the front as it retreats back toward Earth, producing a nested field enhancement signature, as illustrated in Figure 2b. This nested signature is common in the ISEE data in the quasi-perpendicular region of the bow shock and is associated with such out/in motions [e.g., *Russell and Greenstadt*, 1979].

In the following sections we first present the results of the two-spacecraft timing determinations. We then examine in some detail the plasma characteristics of several of the pulsations, including one with a convective signature, one with a nested signature, and several with ambiguous timing signatures. The observations described below confirm the findings of *Greenstadt et al.* [1977] that magnetic pulsations upstream from the quasi-parallel bow shock are the site of slowing and heating of the solar wind plasma. Although we find that the ions are often only weakly heated within the pulsations, we also show examples of very strong ion heating. We further document that the electrons too are appreciably heated within the pulsations. Evidence supporting the existence of a separate interpulsation population of ions is less clear. We do, however, find evidence that coherently reflected ions, which have recently been shown to be an important element of the dissipation in quasi-parallel shocks, appear also to play a role in at least some magnetic pulsations. Finally, the results of the two-spacecraft timing determinations suggest that all three of the possibilities mentioned above (amplified waves versus moving shock surface versus reforming shock) may contribute to the production of magnetic pulsations in the quasi-parallel regime.

OBSERVATIONS

Two-Spacecraft Timing

To perform the two-spacecraft timing of the entry into and exit from the pulsations, one could use any field or plasma parameter which is appreciably different inside the pulsations compared to outside. For the schematic illustrations shown in Figure 2 we have used the total magnetic field magnitude. This is, in fact, the parameter which is employed in the present study because the high temporal resolution of the magnetic field measurements permits us to distinguish small time offsets between the signatures at the two spacecraft. Such a timing capability is necessary to resolve structures which have a correlation length of a few hundred kilometers. We have concentrated on events where the spacecraft separations are sufficiently small that both spacecraft sample essentially the same structure, yet are sufficiently large that the timing difference in the signatures can be resolved. Thus we have examined pulsation events for which the spacecraft separation was in the range of a few hundred kilometers.

One basic result of this study is that both types of timing signatures, namely, convective and nested, are commonly observed. In addition, there are a number of pulsations where the relative timing is ambiguous, either because the time separation is too short to measure, or because the signatures at the two spacecraft are too dissimilar, or the actual entry into the pulsation is difficult to identify. An example of this latter category will be discussed more fully below. Table 1 contains a list of the dates and times of observed pulsations for which we were able to make a fairly certain determination of the two-spacecraft timing. Also given in the table are the spacecraft locations and separation vectors for these events, as well as an indication of the type of signature observed. Table 1 shows that in the sample of pulsations examined there were comparable numbers of nested and convective signatures. On some days the pulsations seemed to be dominantly of one type, whereas on other days we found examples of both types, some within minutes of each other.

Convective Pulsation

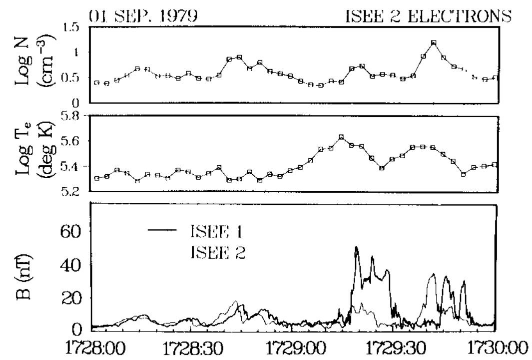

Fig. 3. Magnetic pulsations observed by the ISEE 1 and 2 spacecraft on September 1, 1979. Comparison of the magnetic field traces for the event at ~1729:40 UT shows that ISEE 2, the more sunward spacecraft (Table 1), clearly saw the field enhancement first. Hence the pulsation was convecting antisunward. The upper two panels show the density and electron temperature measured by the ISEE 2 Fast Plasma Experiment. They reveal that the plasma density was well correlated with the field strength throughout the interval and that there was some electron heating associated with the pulsations. The increase in the electron temperature actually precedes the main increase in the field strength and density.

Figure 3 illustrates an example of a pulsation with a convective signature. The bottom panel of the figure shows the magnitude of the magnetic field observed at the two spacecraft, the heavier line corresponding to ISEE 1 and the lighter line corresponding to ISEE 2, while the upper two panels show the density and electron temperature measured simultaneously by the Fast Plasma Experiment on ISEE 2. At the time of these observations ISEE 2 was sunward of ISEE 1, near the nose of the bow shock, and the two were

TABLE 1. Pulsation Events

		S/C Location, R_E			S/C Separation, km				
Date	Time, UT	*X GSE*	*Y GSE*	*Z GSE*	$X_1 - X_2$	$Y_1 - Y_2$	$Z_1 - Z_2$	Convected	Nested
July 9, 1978	0044	2.00	21.20	6.92	−530	36	−207		X
	0047	2.00	21.20	6.92	−530	36	−207	X	
	0106	1.91	21.20	6.89	−531	20	−212		X
July 16, 1978	0226:15	5.11	20.71	7.04	−486	212	−175		X
	0227:30	5.10	20.71	7.04	−487	209	−176		X
July 20, 1978	2020	6.94	20.14	7.05	−411	282	−147	X	
	2023:15	6.93	20.15	7.05	−412	280	−148		X
Sept. 3, 1978	1146:45	14.05	2.64	5.66	−731	−407	−297	X	
	1200:30	14.23	2.78	5.71	−713	−402	−290		X
	1206:30	14.30	2.83	5.73	−706	−401	−288		X
July 19, 1979	0559:30	4.83	21.45	2.94	312	−10	65		X
Aug. 23, 1979	0635	13.95	6.49	4.45	−459	−328	−237		X
	0644:30	14.05	6.60	4.45	−452	−323	−236	X	
	0645:50	14.06	6.61	4.45	−451	−323	−236	X	
Sept. 1, 1979	1723:30	12.71	2.47	4.23	−598	−260	−260	X	
	1729:20	12.80	2.53	4.24	−591	−258	−259	X	
	1729:40	12.80	2.53	4.24	−591	−258	−259	X	
	1732:15	12.83	2.56	4.24	−589	−257	−258	X	
	1746	13.02	2.71	4.26	−575	−254	−258	X	
Total								10	9

S/C is spacecraft.

separated primarily in the X direction (see Table 1). The low-amplitude waves from 1728 to 1729 UT clearly show the expected convective signature of the upstream MHD-like turbulence, with ISEE 1 observing essentially the same field profile as ISEE 2 but at a slightly later time. Examination of the two pulsations observed after 1729:15 UT shows that they too have a convective signature, which can be seen most clearly in the second pulsation. As with the lower-amplitude waves, ISEE 2 observes the field enhancement before ISEE 1. It is interesting to note that the field strength of the first pulsation (starting at about 1729:17 UT) is considerably higher at ISEE 1 than at ISEE 2. This indicates either that the final stage of wave growth occurs very rapidly, in the 2 or so seconds of convection from ISEE 2 to ISEE 1, or that the level of amplification may vary with position transverse to the flow (the spacecraft were separated by about 370 km in the transverse direction (see Table 1)).

Comparison of the upper and lower panels of Figure 3 shows that the plasma density follows the field strength rather closely in these pulsations, as it does in the lower-amplitude waves. In addition, the center panel illustrates that an appreciable increase in the electron temperature was observed within the pulsations. (Indeed, the electron temperature rise preceded the increase in the field strength.) Figure 4 contrasts electron velocity distributions observed within the pulsation (at 1729:41 UT) and outside in the ambient solar wind (at 1728:59 UT). Within the pulsation the distribution is clearly broader and flatter at low energies than it is in the ambient solar wind.

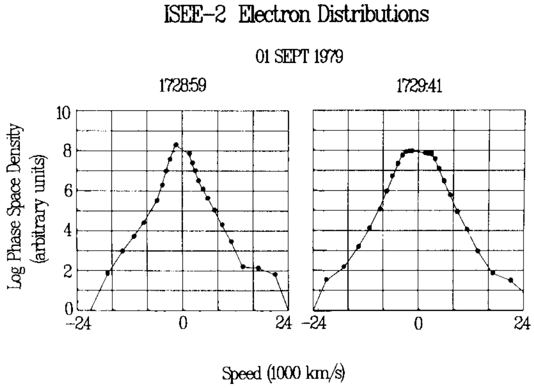

Fig. 4. Cuts through electron velocity distributions observed in the ambient solar wind (left) and within one of the magnetic pulsations shown in Figure 3 (right). The distribution within the pulsation is hotter and flatter at low energies than is the distribution in the ambient solar wind.

The ions also are somewhat heated within the pulsations shown in Figure 3. This is illustrated in Figure 5, which shows contours of constant ion phase space density in two-dimensional velocity space for an interval in the solar wind just before entry into the pulsation (left panel) and another interval within the pulsation itself (right panel). In the ambient solar wind the contours defining the main solar wind ion distribution (centered at ~400 km/s) are very closely spaced. Indeed, the distribution is too cold to be fully resolved by the Fast Plasma Experiment. Within the pulsation, on the other hand, the contours are somewhat more spread out, showing that the ion core is slightly warmer. The flow is also appreciably slower, as the centroid of the distribution has moved to lower velocities.

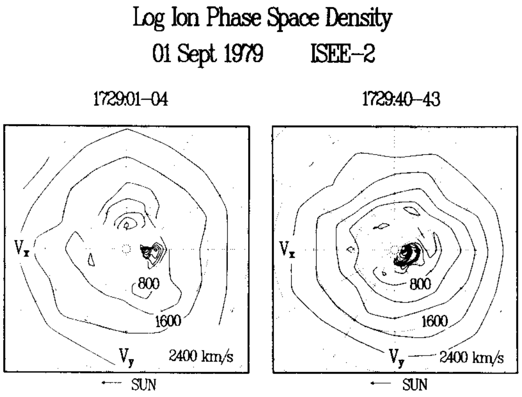

Fig. 5. Contours of constant phase space density in two-dimensional velocity space parallel to the ecliptic plane for ion distributions observed in the ambient solar wind (left) and within the pulsation shown in Figure 3 (right). There are two contours per decade in the plots. Positive V_x corresponds to sunward moving particles, and positive V_y is duskward. The closely spaced contours near $V_x \sim -400$ km/s in the left-hand panel represent the upstream solar wind ion distribution, which is typically too cold to be well resolved by the Fast Plasma Experiment. The contours are more spread out in the distribution on the right, indicating that the ions within the pulsation are somewhat hotter than outside.

These observations are consistent with recent numerical simulations of the nonlinear evolution of upstream low-frequency waves [*Omidi and Winske*, 1989]. Those simulations follow the growth and steepening of an initially low-amplitude wave into a "shocklet" [*Hoppe et al.*, 1981]. Within the shocklet, which continues to convect with the plasma, Omidi and Winske find enhanced density, magnetic field strength, and temperature, as well as a reduced flow speed. They interpret these results as indicating that the waves do indeed steepen into weak, localized shocks which are not stationary with respect to the obstacle in the flow but rather are convected by the solar wind.

Nested Pulsation

Figure 6 shows magnetic field measurements made by ISEE 2 during a 1-hour interval on September 3, 1978, during which several magnetic pulsations were observed. The field magnitude for the pulsation at ~1207 UT is shown in higher time resolution in the lower panel of Figure 7, again with the heavier trace showing the profile observed at

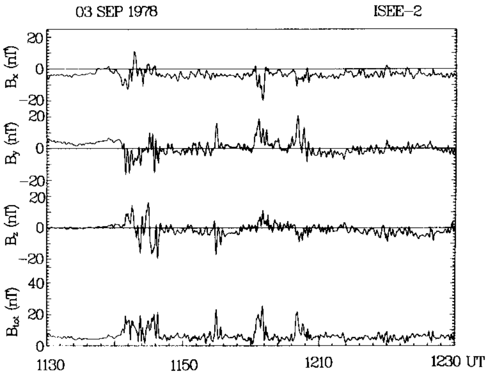

Fig. 6. Magnetic field components (GSE) and total field magnitude for a one-hour interval on September 3, 1978 during which several magnetic pulsations were observed.

ISEE 1 and the lighter trace showing the profile observed at ISEE 2. As in Figure 3, the upper two panels show the density and electron temperature measured by the FPE on ISEE 2. During this interval the spacecraft were again near the nose of the bow shock, with ISEE 2 farthest from the Earth (Table 1). The small-amplitude pulse seen at the very beginning of the interval exhibits the convective signature expected for the upstream waves, with ISEE 2 seeing the field enhancement first. However, the 2-min-long pulsation which extends from roughly 1206:30 to 1208:30 UT quite clearly has a nested signature, with ISEE 1 entering the high-field region first and leaving it last. The nested signature is consistent with a rapid out and in motion of the shock, rather than a simple amplification of the upstream waves. Immediately after the pulsation, there is another small-amplitude wave pulse with a convective signature, followed by a large-amplitude pulsation seen at ISEE 1 but not at ISEE 2.

The pulsation in Figure 7, which appears to be a brief encounter with the shock, bears a number of similarities to the convective pulsation shown in Figure 3. In particular, as with the convective pulsation, the density within the nested pulsation follows the field strength fairly well, and there is again an appreciable amount of electron heating. Another similarity with the convective pulsation in Figure 3 is that the increase in the electron temperature (1206:31 UT) occurs before the jump in the density and field strength. It is interesting to note that the density and field strength do not stay uniformly elevated within the pulsation but rather go quite low in some places. This is also found to be the case in more durable crossings of the quasi-parallel bow shock.

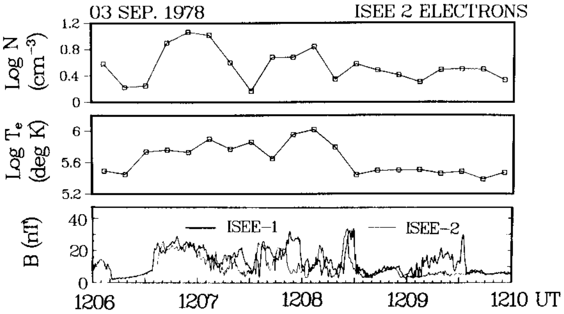

Fig. 7. Magnetic pulsations observed by ISEE 1 and 2 on September 3, 1978 (see Figure 6). Comparison of the magnetic field traces in the lower panel shows that ISEE 1, the earthward spacecraft, entered the field enhancement first and left it last; hence the pulsation is identified as "nested." As was the case for the convective pulsation shown in Figure 3, the density (top panel) and magnetic field strength are well correlated throughout the interval, and the electron temperature (center panel) is elevated throughout the pulsation. Note also that the increase in electron temperature occurs several seconds before the principal increase in the field strength.

Figure 8 shows examples of the particle distributions observed at various times before and during the pulsation of Figure 7. The center row of panels shows two-dimensional velocity space contours of the ion distribution function measured at several different times within the interval, and the panels in the top row show cuts through the corresponding electron velocity distributions. The leftmost panels in both rows were obtained in the relatively cool upstream solar wind just prior to the entry into the pulsation and show the unresolved solar wind distribution plus a weak, isotropic, energetic diffuse component that is present throughout the entire interval. Within the pulsation itself there is a striking variability in the nature of the distributions, especially the ions. The ion distribution measured in the interval 1206:42–1206:45 UT, which corresponds to a region of high field strength and density, has a slightly heated core, quite similar to the ion distribution within the convective pulsation which was illustrated in Figure 5. On the other hand, during the interval 1208:18-1208:21, the ion distribution is very hot, much hotter than in any of the convective pulsations we have identified. This heated distribution occurs in a region of unusually low density and field strength. Indeed, we find that this anticorrelation between ion temperature and magnetic field strength is fairly common within the nested pulsation events we have examined, as well as within more durable crossings into the magnetosheath downstream from the quasi-parallel shock [*Gosling et al.*, 1989].

One intriguing feature of the event shown in Figure 8 is the ion distribution observed in the interval 1207:18-1207:21 UT. This spectrum, nominally from within the pulsation, shows a solar wind ion beam (centered at ~400 km/s) which appears to be essentially unheated, accompanied by an intense and relatively cold secondary population of ions moving in roughly the $+V_y$ direction. The magnetic field strength is somewhat higher than the upstream value during this interval, and the electron distribution is clearly hotter than upstream, with a flattened top at low energies similar to that observed within the convective pulsation discussed above (see Figure 4). Similar ion distributions exhibiting a coherent, secondary beam are often observed within the ramp of the quasi-parallel bow shock [*Gosling et al.*, 1989], suggesting that coherent ion reflection is an important element of the energy dissipation process in the quasi-parallel geometry, just as it is in the quasi-perpendicular geometry (cf. *Gosling and Robson* [1985] and references therein).

What is striking about the 1207:18-1207:21 UT interval in Figure 8 is that it appears in what is nominally the downstream region. A similar occurrence has been noted by *Onsager et al.* [1989] in their survey of coherently reflected ions in the quasi-parallel geometry. These cases reemphasize the observation by *Gosling et al.* [1989] that the observed sequence of ion distributions downstream from the quasi-parallel shock is seldom monotonic. As noted by Gosling et al., such variability in downstream ion distributions suggests the possibility that the shock transition may not be time stationary, as indicated by recent hybrid simulations [*Burgess*, 1989; V. Thomas et al., manuscript in preparation, 1989].

Ambiguous Signatures and Similarity to Hot Diamagnetic Cavities

As mentioned earlier, in the course of this study we examined a number of pulsation events for which it was not possible to determine the two-spacecraft timing unambiguously. An example of a pulsation with a timing ambiguity is illustrated in Figure 9, which shows data obtained on July 19, 1979, when the spacecraft were located just sunward of the dusk terminator. The center panel shows the magnetic field strength observed at the two spacecraft, and the upper and lower rows of panels show the electron and ion distributions, respectively, that were observed at three different times in and near the event.

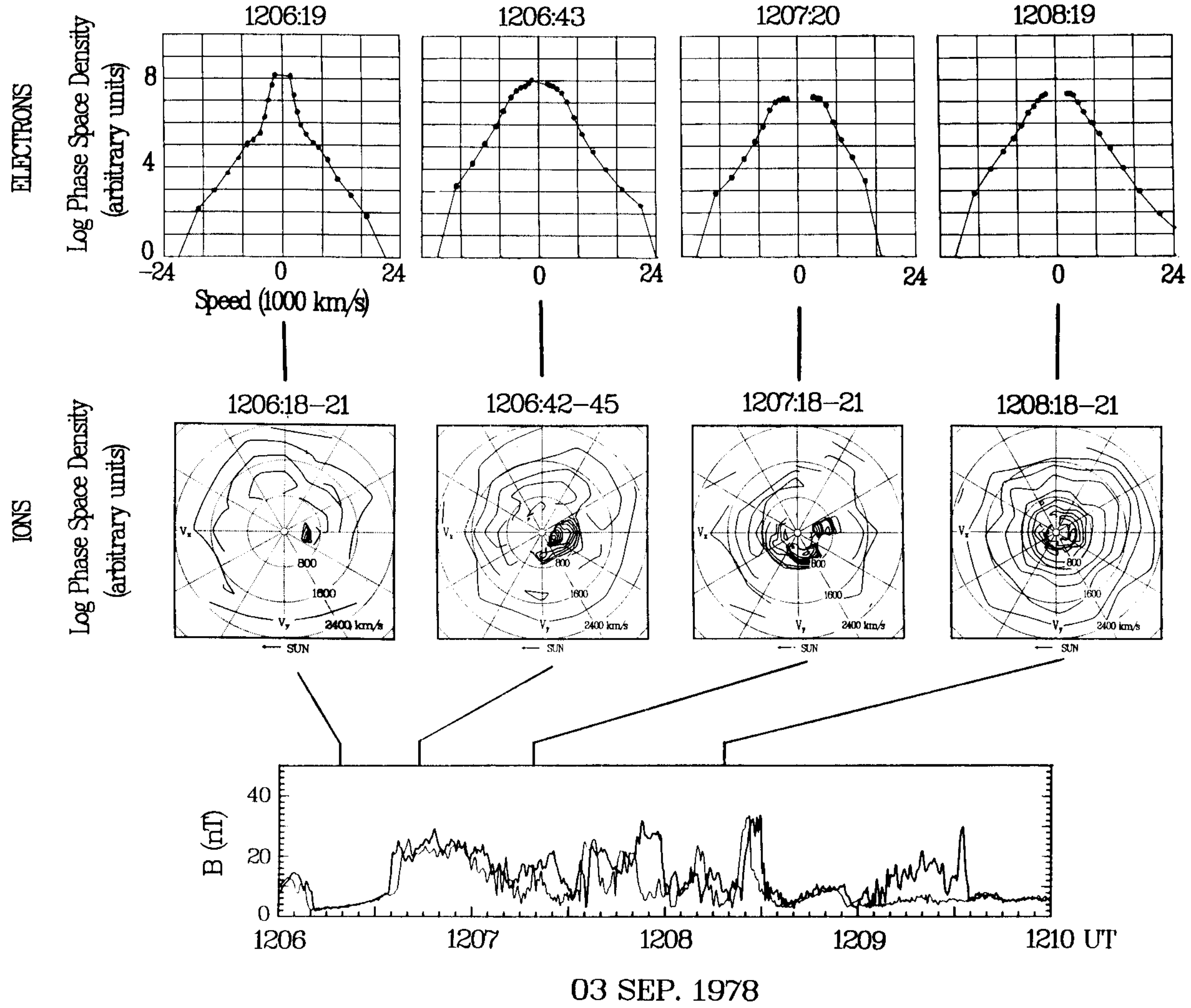

Fig. 8. Ion and electron velocity distributions observed at various points near and within the nested magnetic pulsation shown in Figure 7. The top row of panels shows cuts through the electron velocity distribution at the indicated times, and the center row of panels shows the corresponding two-dimensional contour plots of ion phase space density (same format as Figure 5). The lower panel repeats the plot of the field magnitude at the two spacecraft shown in Figure 7 (ISEE 2 observations are shown as the lighter trace).

At this time, ISEE 1 (heavy trace in the field plot) was located sunward of ISEE 2 (light trace), as can be seen from the convective signature of the low-amplitude waves observed before 0806 UT. The main jump in the field strength associated with the pulsation appeared to occur at about 0806:23 UT. However, for about 10 s prior to that the field had a disturbed character and an unusually low magnitude. Moreover, both the ion and electron distributions within this low-field region were quite hot, as illustrated in the center panels of the top and bottom rows in Figure 9. Indeed, the distributions within the low-field region are considerably hotter than those seen later within the high-field region, which are shown in the last panel of the top and bottom rows. This is another example of the tendency mentioned above for the hottest distributions to be associated with low-field regions within the pulsations, while the particle distributions within the higher-field regions tend to be somewhat cooler. In the event shown in Figure 9, the entry into the pulsation seemed to be signalled by a rise in the temperature of the plasma, rather than by a rise in the field magnitude; there was, however, a slight increase in the field strength which immediately preceded the hot, low-field region, and which was seen slightly earlier by ISEE 1, the sunward spacecraft. Whether this slight rise in the field marked the entry into the pulsation is unclear.

Figure 10 illustrates another event somewhat similar to that shown in Figure 9. From top to bottom are shown the density and electron temperature measured by the FPE on ISEE 2 and the magnetic field traces from both ISEE 1 and 2. During the 4-min interval shown in the figure there are several brief pulsations, some of which appear to have convective timing signatures and some of which have less clear timing. At ISEE 2 there is a slight rise in the field centered at about 0719 UT, followed by a low-field region and then by the main region of elevated field strength. Within the low-field region the plasma density is extremely low, lower than in the ambient solar wind, and the electron temperature is quite high. Although not shown here, the ions are also very hot in the low-field region. Within the subsequent higher-field region, the ions are again somewhat cooler, though still appreciably hotter than in the ambient solar wind.

The magnetic field profiles of the pulsation events shown in Figures 9 and 10 are reminiscent of the field signatures of some of the reported examples of what have been variously called "hot diamagnetic cavities (HDCs)" [*Thomsen et al.*, 1986, 1988; *Fuselier et al.*, 1987], "active current sheets"

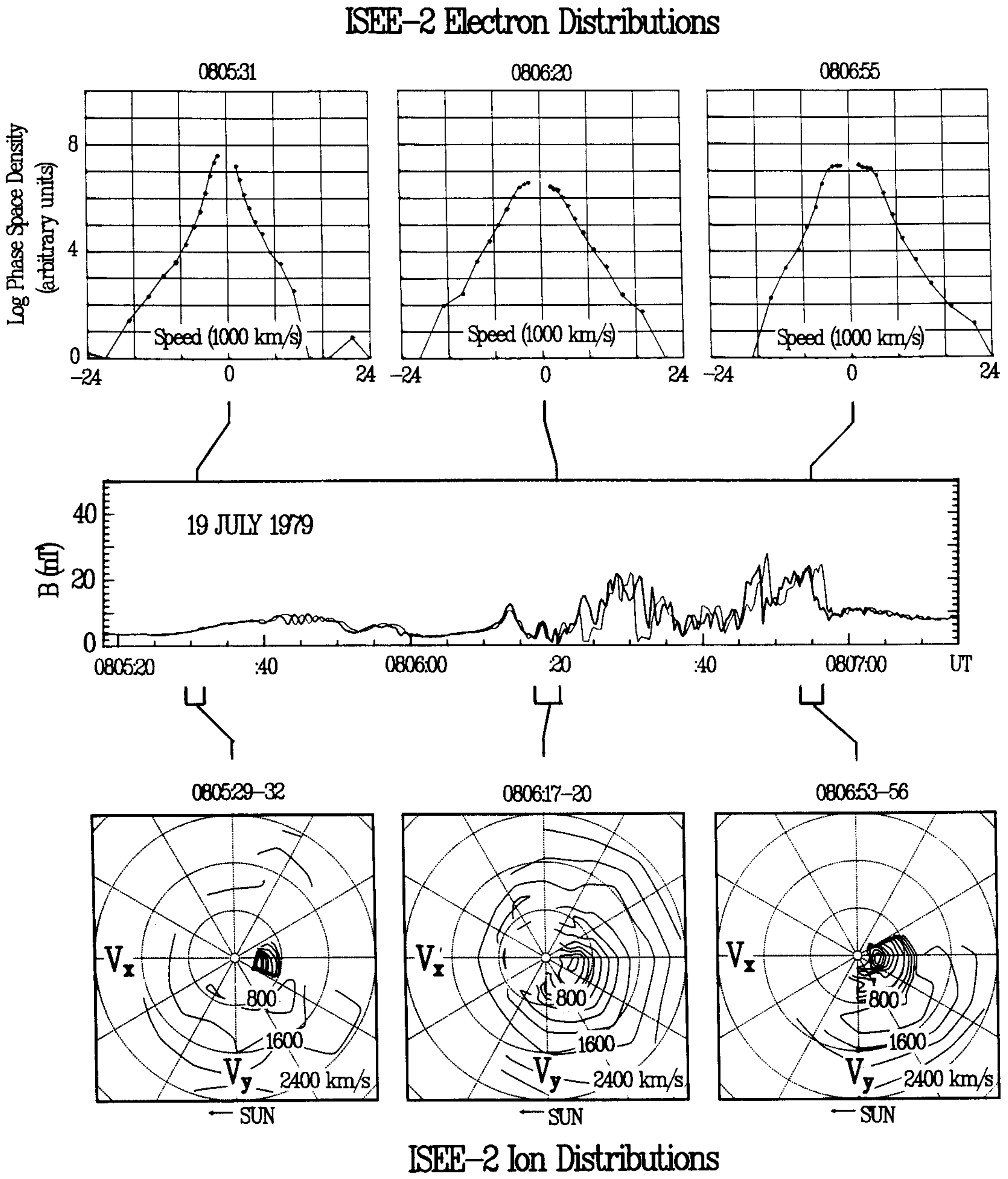

Fig. 9. An example of a pulsation event on July 19, 1979, where the two-spacecraft timing is indeterminate primarily because the particle heating occurs before the main increase in the magnetic field strength. The upper row of panels shows cuts through the electron velocity distribution within the ambient solar wind, within the low-field region preceding the main field increase, and within the trailing high-field region. The lower row of panels shows the corresponding two-dimensional contour plots of the ion distribution function (same format as Figure 5). The center panel shows the magnetic field strength observed at ISEE 1 (heavy curve) and at ISEE 2 (light curve). Both the ions and the electrons were strongly heated within the low-field region at ~0806:20 UT.

[*Schwartz et al.*, 1985, 1988; *Woolliscroft et al.*, 1986], and "three-dimensional plasma structures with anomalous flow directions" [*Paschmann et al.*, 1988]. One might note in particular the similarity to the events observed by the ISEE spacecraft at 0633 UT on November 16, 1977, at 1738 UT on September 28, 1978, and at 0447 UT on November 27, 1978, as presented in Figure 7 of *Thomsen et al.* [1986]. Like the pulsation events in Figures 9 and 10, in those three HDC events the spacecraft first entered a region of hot plasma with lower-than-ambient density, and then entered a somewhat cooler compression region. While many of the identified HDCs have compression regions on both the leading and trailing edges of the hot, low-density region [e.g., *Thomsen et al.*, 1986], these five events show only the trailing compression. The plasma characteristics of the pulsations in Figures 9 and 10 are also quite similar to those of HDCs and HDC-like events. For example, the rounded appearance of the electron distribution observed within the hot, low-density region on July 19, 1979 (Figure 9, top row, center panel) is characteristic of the high-temperature cavities in previously identified HDCs and HDC-like events [*Thomsen et al.*, 1988].

Not only do some magnetic pulsations bear a strong resemblance to HDCs and HDC-like events, but HDCs and HDC-like events commonly occur in close proximity to the more familiar pulsation events. For example, although we

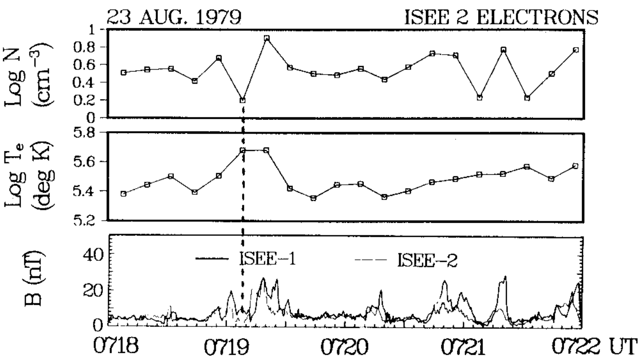

Fig. 10. A second example of a pulsation event for which the two-spacecraft timing is ambiguous primarily because the particle heating occurs before the main increase in the magnetic field (at least at ISEE 2, light trace in lower panel). Within the low-field region the electron temperature is clearly elevated, as is the ion temperature, which is not shown. The density, on the other hand, is appreciably lower than in the ambient solar wind.

did not note it above, the September 1, 1979, pulsations in Figure 1 were followed at about 1750 UT by a hot diamagnetic cavity event which has been previously described in the literature [*Thomsen et al.*, 1988]. Moreover, the pulsation event shown in Figure 7 was followed about 40 min later by one of the first identified HDCs [*Thomsen et al.*, 1986]. As a further example, Figure 11 shows an hour of ISEE 2 observations containing the pulsations presented in Figure 10. The pulsations are embedded in a region of strong wave activity and precede a 5-minute interval when the spacecraft was within the magnetosheath (0727–0732 UT), as indicated by the plasma density, temperature, and flow velocity. Starting at about 0738 UT, there is a curious interval which is characterized by generally high temperatures, densities which are alternately higher than and lower than ambient, strongly slowed and deflected flow, and a peculiar field signature, with large rotations and a magnitude ranging from nearly zero to nearly 6 times the ambient value. Although the very large peak in the magnetic field strength from about 0740 to about 0742 UT does not fit the "classical" description of HDCs from the early reports [e.g., *Thomsen et al.*, 1986], we would nonetheless classify this event as a hot diamagnetic cavity since the event profile is not out of line with the somewhat broader description advocated in subsequent papers. In particular, very large flow deflections were the primary characteristic by which *Paschmann et al.* [1988] and *Schwartz et al.* [1988] identified the events they reported, and the event shown in Figure 11 has flow deflections of more than 120° in some places. In addition to the flow deflection signature, the electron distributions within the first density and field minimum at ~0739 UT (not shown) have the distinctive rounded appearance characteristic of the high-temperature regions in HDCs.

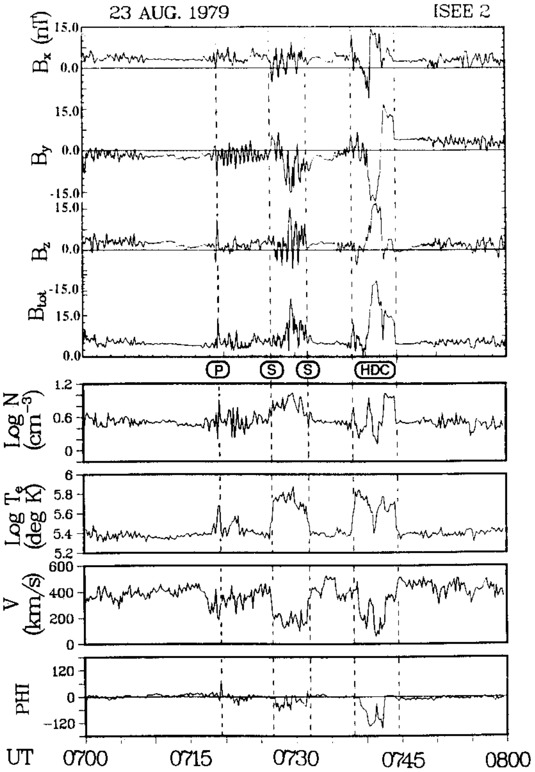

Fig. 11. Magnetic field and plasma observations for one hour containing the magnetic pulsation event shown in Figure 10 (marked *P* between the field and plasma panels). From top to bottom the parameters shown are the GSE components of the magnetic field, total field strength, plasma density, electron temperature, bulk flow speed, and azimuthal angle of the flow in the ecliptic plane (zero is the antisolar direction, positive angles correspond to dawnward flow, and negative angles correspond to duskward flow). Shortly after the pulsation event there is a brief crossing into the magnetosheath, demarcated by the two shock crossings (each marked with an *S*). From about 0738 to 0744 UT there is a strange event in which the temperatures are appreciably elevated, the density and magnetic field strength are alternately higher and lower than is the ambient solar wind, there are large field rotations, and the bulk flow is strongly slowed and deflected, at some points by over 120°. This latter event we classify as a hot diamagnetic cavity (indicated by HDC on the figure). The close proximity of pulsations, shock crossings, and HDCs, along with the strong similarities in many of their properties, suggests that they may be different manifestations of the same basic physical processes.

In the course of this study of pulsations, we have encountered a good many HDC-like events. Few of those events identified in association with pulsations exhibit the classic HDC profile of most of the previously described events [cf. *Schwartz et al.*, 1985, 1988; *Thomsen et al.*, 1986, 1988; *Paschmann et al.*, 1988]. However, they are sufficiently similar that we believe them to be of the same class of phenomena. The relatively common occurrence of these events within the turbulent region upstream from the quasi-parallel shock is in agreement with the prediction of *Thomsen et al.* [1988]: If HDCs are the transient signatures of a process by which collisionless shocks adjust to large changes in the upstream field orientation, then they may be an intrinsic feature of quasi-parallel shocks, which by their very nature must continuously respond to variable upstream conditions.

SUMMARY AND DISCUSSION

We may summarize the results of this study of magnetic pulsations observed upstream from the quasi-parallel bow shock as follows:

1. Comparison of the two-spacecraft magnetic field profiles of the pulsations reveals that both convective and nested signatures can be found (Table 1), in some cases within minutes of each other. Thus it appears that some magnetic pulsations are amplified versions of the convecting upstream waves. Other pulsations appear to be more

nearly at rest in the shock frame and may simply arise from rapid out-and-in motions of the shock itself. The coexistence of pulsations with both types of signatures is consistent with recent numerical simulations of quasi-parallel shocks (*Burgess* [1989] and similar unpublished simulations), which show the upstream waves growing and steepening as they convect toward the shock. As they grow they also appear to convect more slowly until they are nearly standing in the shock frame by the time they arrive at the shock itself. Ultimately the pulses appear to become part of the advancing shock front.

2. Magnetic pulsations, with either timing signature, show evidence of heating, both in the ions and the electrons. Within convective pulsations the ion heating is typically fairly weak. Within nested pulsations the ion heating seems to be quite variable, ranging from weak heating comparable to that observed within convective pulsations to very strong heating. This variation occurs from pulsation to pulsation but also from point to point within a given pulsation. In general, within nested pulsations the hottest distributions tend to occur in regions of lower density and field strength, while the higher field regions tend to be cooler. A similar variation and correlation has been observed downstream from complete quasi-parallel shock crossings [*Gosling et al.*, 1989]. The existence of two fairly distinct plasma regimes both within the pulsations and downstream from the shock suggests that there may be more than one dissipation mechanism operating in the quasi-parallel geometry. A more detailed assessment of this possibility is currently under way.

3. Significant particle heating sometimes occurs before the main jump in the magnetic field and plasma density, complicating the timing of the entry into the pulsation. The electron temperature increase in particular seems not to be well bounded by the region of enhanced field strength (see Figures 3 and 7).

4. Magnetic pulsations bear a number of similarities to hot diamagnetic cavity events and are commonly found in association with them. It seems likely that both types of structures are part of a continuum of phenomena associated with the quasi-parallel shock, including the MHD-like waves, shocklets, and the shock itself. It further seems likely that these various phenomena may be different manifestations of the same basic physical processes. In particular, it appears that ion reflection and the consequent coupling with the solar wind may be an important common denominator. Discrete, cold beams of coherently reflected ions have been observed near HDC-like events [*Thomsen et al.*, 1988], at and near the ramp of quasi-parallel shocks [*Gosling et al.*, 1989; *Onsager et al.*, 1989], and in association with magnetic pulsations (e.g., Figure 8 above). The coupling of reflected ions to the incident solar wind is an effective dissipation mechanism and can potentially provide a variety of plasma states, depending on the beam and solar wind properties (see the discussion by *Thomsen et al.* [1988]). The hypothesis regarding the importance of ion reflection is supported by recent hybrid numerical simulations [*Burgess*, 1989; V. Thomas et al., manuscript in preparation, 1989], which show quasi-parallel shocks to have a cyclical nature, forming and reforming through a process of highly variable ion reflection. In these simulations the reflected ion fraction varies temporally from nearly zero to as much as 50%, resulting in a variety of ion distribution functions, depending on where and when one observes them. One particularly intriguing aspect of these simulations is the possibility of observing a relatively cold solar wind ion population in the presence of a cold reflected ion component in a region of space that one would nominally consider to be downstream of the shock front (V. Thomas et. al, manuscript in preparation 1989). This is remarkably similar to the otherwise puzzling observations shown above in Figure 8 and noted by *Onsager et al.* [1989].

In summary, we believe that evidence presented in this paper and in other recent papers suggests that magnetic pulsations in the quasi-parallel foreshock are manifestations of the basic physical processes which give rise to other quasi-parallel phenomena (e.g., waves, shocklets, hot diamagnetic cavities, and the shock itself). The processes include wave growth, steepening, ion reflection, and the coupling of the reflected and incident ions. The exact interplay of these processes is yet to be elucidated.

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